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LEAK DETECTION AND MEASUREMENT

BY

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SUMMARY

This paper discusses the significant terms used in the field of leak detection and measurement. The various flow modes that may be encountered in leaks are itemized and their characteristics described Discussions are also presented on leak characteristics and special problems such as clogging. Typical instrumentation for leak detection and the specific use for this instrumentation is described.

KEY WORDS

leaks, leakage, calibrated leaks, fluid flow, flow measurement, leakage phenomena

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LEAK DETECTION AND MEASUREMENT - Dr. J. W. Marr

A closely associated problem to sealing technology is that of locating and measuring leakage, since this information is necessary to evaluate the effectiveness of any seal. In this paper, the significant terms used in this field are defined and illustrated. Discussions are also presented on major flow phenomena, and special problems such as clogging. Typical instrumentation for leak detection is described.

1. Definitions

The literature in the field of leak detection is cluttered with different nomenclature and sets of units. Important nomenclature is defined as follows:

a. Leak

In vacuum technology, a hole or porosity in the wall of an enclosure capable of passing gas from one side of the wall to the other under pressure or concentration differential existing across the wall(Ref.1).

A leak is not usually indicated by certain dimensions. Rather,it represents a physical hole of a certain length and width. However, since a leak is not intentionally manufactured into an item, its dimensions are generally unknown. In leak detection the dimension used to describe the leak is the leak rate.

b. Leak or Leakage Rate

The leak or leakage rate is defined as the rate of flow through a leak with gas at a specified high pressure (usually atmospheric pressure) on the inlet side and gas at a pressure on the exit side which is low enough to have little effect on the leakage rate. The units of leak rate are:

$$\frac{\text{Pressure x Volume}}{\text{Time}}$$

This is occasionally referred to as mass flow. At a constant temperature, this unit is proportional to the mass flow rate. In describing a leak, the nature of the leaking gas and its temperature are usually known, so that using the formula:

$$PV = \frac{g}{M} RT^{★} \qquad \text{Eq. 1}$$

where P = Pressure
V = Volume of Cylinder
g = Mass of the Gas
M = Molecular Weight
R = Gas Constant
T = Absolute Temperature

The actual leakage mass may be determined by:

$$g = \frac{PVM}{RT} \qquad \text{Eq. 2}$$

c. Units

In scientific work on leaks, mass flow is usually expressed in Torr* x liters/sec or atm x cc/sec at 25°C. In engineering work a wide variety of units for leakage are used. The justification for this diversity of units is the relative ease with which this variety of units can be adapted to individual engineering problems. For example, an operator has a gas cylinder with a pressure gauge calibrated in lb/sq in. If this operator reads the gauge daily, it is convenient for him to express the leakage as:

---

* - A Torr is the suggested international standard to replace the English term millimeters of mercury. A Torr is defined as 1/760 of a standard atmosphere and differs by only one part in seven million from the International Standard millimeter of mercury.

★ - A list of symbols appears at the end of this paper.

$$\frac{\text{pressure difference x cylinder volume}}{\text{time increment}} \quad \left(\frac{\text{psi x ft}^3}{\text{day}}\right)$$

Because of the variety of these units, conversion factors have been included in Table 1 (at end of this paper).

Leakage rate discussions are further complicated by the use of units of mass instead of pressure x volume/time units. Equation 2 can be used for conversion in this case.

d. Modes of Flow

The leakage of fluid occurs by a variety of flow mechanisms: permeation, molecular flow, laminar flow, transition flow, turbulent flow and choked flow. These, as well as the circumstances leading to this flow, will be described in this section.

Although the flow characteristics of a leak may be expressed in many ways, the most common is in terms of conductance of the leak. Conductance is defined by:

$$C = \frac{Q}{P_2 - P_1} \qquad \text{Eq. 3}$$

where C = Conductance

Q = Mass Flow

P_2-P_1 = The Pressure Drop Across the Leak

Conductance has the dimensions of volume/unit time and may be thought of as the volume of gas that enters the leak/second. Conductance is the flow rate-pressure x volume/unit time divided by pressure drop.

The net conductance of a channel (C) is given by the following equation:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \frac{1}{C_n} \qquad \text{Eq. 4}$$

where C_1, C_2, C_3, etc., are the conductances of various lengths of the channel in series. The above equation shows that a constriction with an unusually low conductance will cause a very large constriction factor in the flow of liquid. Conductances and their influence on flow are discussed in the following subsections.

i. **Permeation**

Permeation is passage of a fluid into, through, and out of a solid barrier having no holes large enough to permit more than a small fraction of the molecules to pass through any one hole. The process always involves diffusion through a solid and may involve other phenomena such as adsorption, dissociation, migration and desorption.

The general formula for permeation is:

$$Q = K_p A \frac{\Delta P}{\ell} \qquad \text{Eq. 5}$$

where Q = Rate of Flow

K_p = Permeation Rate Constant

A = Area Normal to Flow

ΔP = Pressure Drop Along the Flow Path

ℓ = Length of Flow Path

Permeation was described as a separate subject in Appendix A. TIS Report 63GL100.

ii. Molecular Flow

Molecular flow is defined as flow through a duct under conditions such that the mean free path is greater than the largest dimension of a transverse section of the duct. (Ref.1) In such a flow, each atom moves independentally by random movement from a volume of high to one of low concentration.

The mean free path is the average distance that a molecule travels between successive collisions with the other molecules of an ensemble. The mean free path λ is:

$$\lambda = \frac{1}{\sqrt{2}\pi n\sigma^2} \qquad \text{Eq. 6}$$

where n = Number of molecules in a unit volume
σ = Molecular diameter

If $n = \frac{gA^o}{MV}$ Eq. 7

where g = Mass of the gas
A^o = Avogadro's number; i.e. number of molecules per mole
M = Molecular weight of the gas
V = Volume

and replacing V from Equation 1 the value in Equation 7 we obtain:

$$\lambda = \frac{RT}{\sqrt{2}\pi PA^o\sigma^2} \qquad \text{Eq. 8}$$

Equation 8 shows that at constant pressure, the mean free path is proportional to temperature. However, if the amount of gas in a volume is kept constant, the mean free path is independent of temperature (Equation 6).

The magnitude of molecular diameters and mean free paths are shown in Table 2 (at the end of this paper). As a convenient calculation guide, the mean free path of air at room temperature is:

$$\lambda \text{ air} = \frac{5 \times 10^{-3}}{P} \text{ centimeters} \qquad \text{Eq. 9}$$

when P is expressed in Torr.

The original mathematical derivations of molecular flow are attributed to Knudsen (Ref.2). The rate of flow in a long pipe is:

$$Q = \frac{\sqrt{2\pi}}{6} \sqrt{\frac{RT}{M}} \frac{d^3}{\ell} (P_2 - P_1) \qquad \text{Eq. 10}$$

where d = The diameter of the pipe
ℓ = The length of the pipe
P_2 and P_1 = The pressures at the two ends

For this formula to apply, the pipe must be of a circular cross-section. For pipes and ducts of a non-circular cross-section the conductance is less than for pipes of circular cross-section and equal area. Equation 10 applies only if the pipe is much longer than its diameter. Any difficulty experienced by a molecule in entering the pipe must be negligibly small compared to the difficulty in traversing its length. If difficulty is experienced in entering the pipe, the kinetic theory shows that the rate of free molecular escape of gas from the container into a small aperature of area A is:

$$Q = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{RT}{M}} A (P_2 - P_1) \qquad \text{Eq. 11}$$

In the case of an aperature, using the formula given above the opening does not have to be circular.

In molecular flow, the conductance of lines and aperatures is independent of pressure. Calculations may be made of the effect of turns, apertures, and change in pipe diameter to calculate the overall flow in a leak. Formulas are available in the literature (Refs.3 and 4) on the effect of structure on the leakage rate.

iii. Laminar Flow

The laminar flow of a fluid in a pipe is defined as a condition when the velocity distribution of the fluid in the cross-section of the pipe is parabolic. Laminar flow is one of the two classes of viscous flow, the other class being turbulent flow. Because turbulent flow is rarely encountered in leaks, the term viscous flow is sometimes incorrectly used to describe laminar flow in leak detection work.

The most familar viscous flow equation is one developed by Poiseuille (Ref. 5) for the flow through a straight tube of a circular cross-section.

$$Q = \frac{\pi}{8}\left(\frac{d}{2}\right)^4 \frac{P_a}{\eta \ell} (P_2 - P_1) \qquad \text{Eq. 12}$$

where η = The viscosity of the gas

P_a = The arithmetic mean between P_2 and P_1

In the range where that equation is applicable, it has been substantially verified experimentally. The viscous conductance of the tube by definition of Equation 3 is:

$$C = \frac{\pi}{8}\left(\frac{d}{2}\right)^4 \frac{P_a}{\eta \ell} \qquad \text{Eq. 13}$$

Laminar flow takes place when the Reynolds' number of flow is lower than a defined critical value. The Reynolds' number is a unitless quantity which defines the flow conditions and is given by:

$$N_{Re} = \frac{d\rho F}{\eta} \qquad \text{Eq. 14}$$

where N_{Re} = The Reynolds' number
ρ = The fluid density
η = The absolute viscosity
F = The average flow velocity across a plane in the tube

By substituting the ideal gas equation in the above formula we obtain the expression for the Reynolds' number of a gas as

$$N_{Re} = \frac{Q}{d}\left(\frac{4M}{\pi\eta RT}\right) \qquad \text{Eq. 15}$$

The critical value of Reynolds' number has been shown to be dependent upon the entrance conditions, roughness of the walls of a tube, and shape of the flow path. In general for smooth tubes, with well rounded entrances, the critical value is about 1,200. For flow corrections due to turns, constrictions, and surface roughness refer to Ref. 6 and 7.

The kinetic theory states that the viscosity of a gas is given by the relationship (Ref. 8):

$$\eta = \frac{m\bar{F}}{3\sqrt{2}\pi\sigma^2} \qquad \text{Eq. 16}$$

where $\bar{F}$ = Average velocity of the individual molecules
m = Their mass
σ = Their diameter

The average velocity of a molecule is:

$$\bar{F} = \left(\frac{8RT}{\pi M}\right)^{1/2} \qquad \text{Eq. 17}$$

the mass of the individual molecules is:

$$m = \frac{M}{A^{o}} \qquad \text{Eq. 18}$$

Substituting Equation 17 and 18 in Equation 16 we obtain:

$$\eta = \frac{2(MRT)^{1/2}}{3\pi^{3/2} A^{o} \sigma^{2}} \qquad \text{Eq. 19}$$

It may be seen from the above equation that the viscosity of a gas is independent of pressure and is proportional to the square root of temperature.

iv. Transition Flow

The transition from laminar flow to molecular flow is gradual. The mathematical treatment of this region is extremely difficult. However, a treatment of this region is necessary because a leak from a volume to a vacuum necessarily involves a transition from laminar to molecular flow. Equation 10 shows that the conductivity of a passage in molecular flow is proportional to the cube of the passage diameter and independent of pressure. Conversely Equation 13 shows that the conductivity of the same passage in laminar flow is proportional to the fourth power of the diameter of passage and proportional to the pressure. In viscous flow the mixture of gases travels at a rate inversely proportional to the viscosity of this mixture and no separation of gases takes place. However, in molecular flow the rate of flow of the individual gases present in a gas mixture is inversely proportional to the square root of their individual masses. Therefore a certain amount of separation takes place through a leak.

Knudsen (Ref. 2) derived a semiempirical formula for the flow of gases through long tubes in the transition region. This formula is:

$$C = \left[\frac{\pi}{8}\left(\frac{d}{2}\right)^4 \frac{P_a}{\eta \ell}\right] + \left[\frac{1}{6}\sqrt{\frac{2\pi RT}{M}}\frac{d^3}{\ell}\right]\left[\frac{1+\sqrt{\frac{M}{RT}}\frac{dP_a}{\eta}}{1+1.24\sqrt{\frac{M}{RT}}\frac{dP_a}{\eta}}\right] \qquad \text{Eq. 20}$$

The formula is valid providing that

1. the flow is not turbulent in any part of the pipe.
2. the pressure difference between the ends is not so great that the mechanism of flow (i.e. viscous or molecular) changes along the pipe.

Although the first of these conditions is usually satisfied in the leak, the second generally is not; that is the transition from viscous to molecular flow does take place. The above equation at low pressures becomes an equation of molecular flow; whereas at high pressure this equation reduces to one of strictly laminar flow.

Knudsen used the above equation to represent his experimental data. The equation which has the effect of molecular flow added to the effect of laminar flow is not an actual representation of the flow mechanism taking place in the leak. For that reason the restriction, that the pressure difference between the two ends is not large, is necessary, i.e., change of flow mode does not take place. An addition of the two effects is not a true representation since the same amount of fluid which travels part of the pipe as laminar flow will eventually travel via the molecular flow mode. Other authors have (Refs. 9, 10)attempted to derive equations to represent this phenomenon of transition from one type of flow to another, however, none of them have been successful. One satisfactory method (Ref.11) is to calculate viscous flow through one section of the tube, molecular flow through another,and approximate the in between region.

v. Turbulent Flow

Above a critical value of the Reynolds' number(about 2100 in the case of circular pipe flow)flow becomes unstable resulting in innumerable eddies or vortexes in the flow. Any particle in turbulent flow follows a very erratic path, whereas in laminar flow the particle follows a straight line.

The laws for turbulent flow are quite different from the laws for laminar flow. The equation relating mass flow rate (Q) in units of pressure x volume/time may be written:

$$Q = \pi d^{5/2} \left[\frac{RT(P_2^{\,2} - P_1^{\,2})}{16 fM\ell} \right]^{1/2} \qquad \text{Eq. 21}$$

where f, the friction factor, is defined on p.125 of Ref. 7. The friction factor depends on roughness of the channel walls, and can be considered a constant in fully developed turbulent flow.

Turbulent flow, because it requires relatively high velocity, probably occurs only in rather large leaks.

vi. Choked Flow

Choked flow, or sonic flow as it is sometimes called, occurs under certain conditions of geometry and pressure. Assume there exists a passage in the form of an orifice or a venturi, and assume that the pressure upstream is kept constant. If the pressure downstream is gradually lowered, the velocity through the throat or orifice will increase until it reaches the speed of sound through the fluid. The downstream pressure at the time the orifice velocity reaches the speed of sound is called the critical pressure. If the downstream pressure is lowered below this critical pressure, no further increase in orifice velocity can occur, with the consequence that the mass flow rate has reached its maximum. This condition is known as "choked" or "sonic" flow.

Choked flow can occur under the following two conditions: (1) the flow passage must be in the form of an orifice or venturi, in which only negligible frictional losses occur upstream of the orifice or throat of the venturi; (2) the ratio of downstream to upstream pressure must be below a certain "critical" value, which is

$$r_c = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \qquad \text{Eq. 22}$$

The velocity of sound through a gas can be written:

$$F_c = \sqrt{\frac{2\gamma}{\gamma+1} \quad \frac{RT_1}{M}} \qquad \text{Eq. 23}$$

where F_c = Velocity of sound

T_1 = Absolute temperature upstream of the orifice where the velocity is low

$\gamma = C_p/C_v$ Eq. 24

where C_p = Heat capacity at constant pressure

C_v = Heat capacity at constant volume

The mass flow rate under a choked flow conditions is:

$$Q = \frac{\pi d^2 P_1}{4} \sqrt{\frac{2\gamma}{\gamma+1} \quad \frac{RT_1}{M}} \qquad \text{Eq. 25}$$

where d = Orifice diameter

P_1 = Upstream pressure

For an ideal monatomic gas, the value of γ is 1.67. For polyatomic molecules, the heat energy supplied is used for increasing not only the kinetic energy of translation, but also the kinetic energy of rotation and vibration. Since the same amount of extra energy is required at both constant pressure and constant volume, γ decreases with molecular complexity. Characteristic values of γ are shown in Table 3 (at the end of this paper). Additional values may be calculated (Ref. 12) or obtained from other references (Ref. 13).

vii. Distinction Between Modes of Flow

In the above subsections, the equations have been presented for the various possible modes of flow that can be encountered in a leak. The following rules may be used to predict the mode most likely to occur. In distinguishing between laminar and molecular flow the size of the passage and the mean free path are the two important parameters. The distinction may be specified by a dimensionless parameter called the Knudsen number. The Knudsen number is defined as the ratio of the mean free path of the molecule to a characteristic dimension of the channel through which the gas is flowing.

$$N_K = \frac{\lambda}{d} \qquad \text{Eq.26}$$

where N_K = Knudsen number

λ = Mean free path

d = Channel diameter

The type of flow encountered in the various Knudsen number ranges is shown in Equation 27.

$$\begin{aligned} &\frac{\lambda}{d} < 0.01 \text{ laminar flow} \\ &\frac{\lambda}{d} > 1.00 \text{ molecular flow} \qquad \text{Eq. 27} \\ &0.01 < \frac{\lambda}{d} < 1.00 \text{ transition flow} \end{aligned}$$

Flow in the viscous region is determined by the Reynolds' number which was described both in Equation 15 (the following) and in subsection iii.

$$N_{Re} = \frac{d\rho F}{\eta} \; \frac{Q}{d} \left(\frac{4M}{\pi \eta RT} \right) \qquad \text{Eq. 15}$$

The distinction between laminar and turbulent flow is shown in Equation 28.

$N_{Re} > 2100$	Turbulent flow	
$N_{Re} < 1200$	Viscous flow	Eq. 28
$1200 < N_{Re} < 2100$	Either turbulent or viscous depending on duct conditions	

In choked flow, the flow takes place when the pressure ratio between outlet and inlet reaches a certain minimum value. This of course is dependent on other characteristics such as aperature dimension, etc. The formula for the critical pressure ratio is defined by Equation 29.

$$r = \frac{P_2}{P_1} \qquad \text{Eq. 29}$$

The critical ratio, the ratio below which choked flow takes place is:

$$r_c = \left(\frac{2}{\gamma+1} \right)^{\gamma/\gamma-1} \qquad \text{Eq. 22}$$

Choked flow cannot take place when P_1 is so low that molecular flow exists.

2. Conversion of Measured Leakage to Standard Leakage Rate

Converting leakage measured on a detector to the amount of leakage anticipated when the container is filled with working fluid is a difficult problem. The problem consists of three general categories. The inability to obtain a mathematical correlation between the measured leakage and the anticipated one, the inability to obtain a good standard leak and the difficulty experienced due to clogging. These problems will be discussed individually in the following subsections.

a. Mathematical Correlation of Leak Test Results

In the preceding section entitled 'Modes of Flow' the mathematical equations describing the various types of fluid flow were presented. If the physical dimensions of the leak were known, it would be easy to calculate the anticipated leakage rate during working conditions from the leakage rate measured on a detector. A leak is not usually built into a system. For this reason its dimensions are rarely known. Even if all the dimensions were known, the flow mode still has to be ascertained. To define the flow mode the geometry of a leak has to be known. However, this is usually not the case. Another approach to this problem is to assume the leak dimensions and flow mode remain constant. Therefore, the flow rate will be dependent upon pressure. In Equation 30 the dependence of flow rate on pressure is shown in four different modes of flow:

Molecular $Q \propto \frac{P}{\sqrt{M}}$ Eq. 30a

Laminar $Q \propto \frac{P^2}{\eta}$ Eq. 30b

Turbulent $Q \propto \frac{P}{\sqrt{M}}$ Eq. 30c

Choked $Q \propto \frac{P\sqrt{\frac{\gamma}{\gamma+1}}}{\sqrt{M}}$ Eq. 30d

Also placed in the above equations are the physical constants of the fluids which affect the above flow properties. When using the above equations the flow mode in a leak may change during a change of pressure or constants of the gas.

Working with a variety of leaks of different sizes and under different conditions, some of the above equations may readily be eliminated. For example, if the leak rate is small, it is relatively easy to assume that no turbulent flow will take place. If the leak is one going from high pressure to a slightly lower pressure,but not a vacuum, it is likely that molecular flow is not the flow mechanism. In the above case, the flow may be of either a choked or laminar flow nature and therefore conversion to a second flow pressure is relatively easy. However, in this particular case conversion to a different gas is not as easy since this leaves the choice of converting as a function of either heat capacity differences, which might be negligibly small (Equation 30d), or viscosity ratios which conceivably could be large(Equation 30b).

Another example - convert one leakage rate flowing into a vacuum to an anticipated rate of a different pressure into the same vacuum. Calculations described in (Ref. 10), show that if the leak is of relatively small size (10^{-5} atm cc/sec or less) the molecular flow will play a major role in such a leak. However should the leak be relatively large (10^{-3} atm cc/sec or greater) the leakage will be predominately of laminar nature. If one can accurately predict the type of flow which will predominate in the leak, one could therefore make accurate conversions to a different set of conditions. Unfortunately the state-of-the-art is such that these predictions are usually not possible.

An attempt to derive a general method for leak conversion is described in the paper by Santeler and Moller (Ref. 14). These authors use the viscous and molecular flow equations to develop a graphical method of leakage conversion. The above approach was tested on gaskets recently being used in the Advanced Technology Laboratories. The Laboratory is currently performing the work on another NASA Contract (NAS 8-4012) in an attempt to develop zero leakage fluid connectors for liquid rocket propellant transmission lines. On this contract a large number of gaskets are subjected to a gradually increasing helium pressure and the leakage rate very carefully measured with a modified helium leak detector. In this way, leakage rate at a variety of pressures is measured. The results of these experiments were compared with predictions made by the graphs developed by Santeler and Moller. It was found that in approximately half the experiments the leakages predicted were correct. The results which were in error, were so by as much as one order of magnitude, both positive and negative. Some explanations for these devriations are given in TIS Report 64GL163.

b. Limitations of Standard Leaks

One of the difficulties encountered in leak detection calibration techniques is the difficulty of obtaining a proper leak standard. It is possible to purchase from a number of vacuum equipment manufacturers a calibrated leak. These leaks are calibrated to an outflow of a particular gas at a particular working pressure. In such a leak, an operator using a leak detector is able to calibrate his instrument, to determine the magnitude of an unknown leakage. Unfortunately most of these leaks are calibrated for only one gas at one pressure difference. Since the flow mode is unknown a good mathematical relationsip is not available for its behavior at another pressure or gas without performing actual tests. For example, General Electric Company produces a calibrated leak by collapsing a metal capillary tube. This type of calibrated leak may be made to a leakage rate as small as 10^{-7} atm cc/sec. Although smaller leaks have been manufactured by this technique they are extremely difficult to produce, and even more difficult to keep from clogging (clogging is discussed in the next section). If this leak is calibrated with a couple of gases at several different pressures, it might be possible to determine if the flow exhibited is of viscous, choked,or molecular nature. Therefore, it would be possible to determine the mathematical relationships to extrapolate to a different set of pressure differences. If it can be determined that the flow mode is the same in both the existing leaks and in the standard leak, then the standard leak may be placed in the operating conditions to determine the anticipated leakage rate without extensive mathematical calculations.

If a calibrated leak is required with a leakage rate smaller than 10^{-7} atm cc/sec, the leak has to be manufactured in a different manner. Small leaks are made from a sintered glass plug, or sometimes by utilizing the principle of permeation. The mechanism of flow in such a leak will be different from the flow in the long crack or seal face. Therefore, a calibrated leak of this small leak rate can only be used to calibrate instruments.

c. Computation of Theoretical Leak Size

In an attempt to determine the order of magnitude of the physical size of leaks, Knudsen's semiempirical equation was used by R. Loevin and A. Guthrie (Ref. 15) for the flow of gas through a capillary in t transition region. The conductance, as shown in Equation 20 is:

$$C = \left[\frac{\pi}{8}\left(\frac{d}{2}\right)^4 \frac{P_a}{\eta \ell}\right] + \left[\frac{1}{6}\sqrt{\frac{2\pi RT}{M}}\,\frac{d^3}{\ell}\right]\left[\frac{1+\sqrt{\frac{M}{RT}}\,\frac{dP_a}{\eta}}{1+1.24\sqrt{\frac{M}{RT}}\,\frac{dP_a}{\eta}}\right] \qquad \text{Eq. 20}$$

This equation may be rewritten in the form:

$$C = \frac{1}{\Delta \ell}\left[aP + b\,\frac{1+jP}{1+hP}\right] \qquad \text{Eq. 31}$$

where $\Delta \ell$ is the length of the short segment in which the average pressure is P and the pressure drop is ΔP. The flow through such a segment is based on Equation 3:

$$Q = \left(aP + b\,\frac{1+jP}{1+hP}\right)\frac{\Delta P}{\Delta \ell} \qquad \text{Eq. 32}$$

Integrating Equation 32 over the length of the capillary:

$$Q = \frac{1}{\ell}\int_{P_2}^{P_1}\left(aP + b\,\frac{1+jP}{1+hP}\right)dP = \qquad \text{Eq. 33}$$

$$= \frac{1}{\ell}\left[\frac{a}{2}\,P^2 + \frac{bjP}{h} + \frac{b(h-j)}{h^2}\ln\left|1+hP\right|\right]_{P_2}^{P_1}$$

where $a = \frac{\pi}{8\eta}\left(\frac{d}{2}\right)^4$

$b = \frac{1}{6}\sqrt{\frac{2\pi RT}{M}}\,d^3$

$j = \sqrt{\frac{M}{RT}}\,\frac{d}{\eta}$

$h = 1.24\sqrt{\frac{M}{RT}}\,\frac{d}{\eta}$

Flow Q is a constant in a steady state condition.

This is an elegant use of Knudsen's equation for transition flow. In the differential, change in flow mode does not take place, thus following one of the important rules of Knudsen's derivation. However, a change of flow mode takes place between the entrance and the exit of the tube, but this is a result of integrating the equation. The results of these calculations for air are shown on Table 4. (at the end of this paper).

The calculations to obtain Table 4 assumed that the pressure inside the hypothetical cylindrical leak dropped to a low value P_2 which is negligible as compared to the atmospheric pressure. Inside the leak the velocity of the gas will rise from some small value at the inlet to a maximum value not greater than the velocity of sound under the prevailing temperature and pressure conditions. According to kinetic theory the velocity of sound in any gas is:

$$F_c = \sqrt{\gamma \frac{P}{\phi}} \qquad \text{Eq. 34}$$

where γ = Ratio of heat capacities
P = Pressure
ρ = density

Then if isothermal expansion is assumed, it follows from the isothermal equation of state:

$$P = \rho \frac{RT}{M} \qquad \text{Eq. 35}$$

$$F_c = \sqrt{\gamma \frac{RT}{M}}^{\,*} \qquad \text{Eq. 36}$$

---

*Equation 36 differs from Equation 22 because the temperature in the latter is an upstream temperature prior to adiabatic expansion. In Equation 36 the gas temperature is expressed at the same point as the velocity.

the velocity of sound in a gas at constant temperature is constant. These minimum pressures in the leak were calculated and given in column P_2 in Table 4. The implication of the pressure calculations is that the flow reaches a sonic velocity. Therefore a choked flow mode situation exists somewhere in the leak, unless the pressure P_2 is so low that the flow is molecular. Calculations cannot be made in this manner for tube diameters larger than 10^{-2} centimeters because at this point the Reynolds' number is high enough to produce turbulent flow.

It may be seen from Equation 17 that the difference between flow of air and flow of other gases is dependent on their molecular weight and viscosities. The upper and lower limits of flow corrections for other gases applicable to the calculations are presented in Table 4 (at end of this

These calculations were entered by Loevinger and Guthrie, as a general guide and not as ultimate figures. Of course in an actual leak the holes are neither circular in diameter or of a constant diameter. However we may obtain a certain insight as to the properties of the leak from the numbers in Table 4.

The Special Problem of Clogging

The Advanced Technology Laboratories of the General Electric Company perform a service of non-routine leak checking for the General Electric Schenectady Plants. Certain properties of leaks are commonly observed in the performance of this service. The leak testing is generally done with a helium mass spectrometer leak detector having sensitivities of approximately 10^{-10} atm cc/sec.

A phenomenon frequently observed is that if a container to be tested for leaks has at any time after manufacture been in contact with a liquid, no leaks small in size (i.e. 10^{-7} atm cc/sec or smaller) will be found. The explanation for this is that the small leaks are clogged with liquid due to its surface tension. If water has entered a capillary tube, the pressure necessary to force it out of the tube is given by the following equation (Ref. 16):

$$P = \frac{4\phi}{d} \qquad \text{Eq. 37}$$

where ϕ = surface tension of the liquid usually expressed in dynes per centimeter

d = tube diameter in centimeters

P = pressure expressed in dynes/cm^2 *

Referring back to Table 4, a leak with a diameter of 1×10^{-4} centimeters will have a leakage rate for helium of approximately $1.3 \times 10^{-6} \ell$ atm/sec. If water, with a surface tension of 72 dynes/cm, enters such a leak, the pressure required to force it out is approximately 2.8 atmospheres. Since the pressure differential during leak testing is only 1 atmosphere, this leak is essentially clogged by the use of water. In actual conditions clogging is more likely to take place than in the above example. Most leaks are neither circular or regular in diameter. They usually contain constrictions and occasionally consist of slits. The rate of flow in a leak is

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*One atmosphere is equal to 1.063759×10^{6} dynes/cm^2

approximately proportional to the leak cross-sections. If clogging were to take place, the pressure required to remove a liquid is inversely proportional to the smallest dimension in the cross-section. Therefore, clogging of an orifice or of a slit is more likely to take place than may be assumed from the above example. If the leak in the above example were in fact a slit with the ratio of width to height of 10 to 1, the pressure necessary to remove water from such a slit would be approximately 28 atmospheres. Leakage would be of the same order of magnitude as mentioned in the above example.

Unfortunately, such clogging is not of a permanent nature. If the temperature of the container were to be raised, the surface tension of the liquid decreases and quite possibly the liquid inside the leak evaporates. Because of this phenomenon, the Vacuum Laboratory does not test with soap solution or liquid on parts which are then going to be subjected to a baking procedure. The opening up of these clogged leaks is an extremely slow process, since the evaporation will take place at a rate similar to the leakage rate.

It is, generally observed that leakage much smaller than 10^{-8}atm cc/sec are rarely seen. Such leakages are in the range of detectability, but are a rare phenomenon when found. When found the equipment on which they were located was new and had never been in contact with a liquid. These leaks have to be carefully treated or they will clog during normal handling. From Table 4 it may be seen that a leak 10^{-8} atm cc/sec has a diameter in the order of 10^{-5} centimeters. To place this number in dimensions of atomic size, its diameter is about 1,000 Angstrom units.* Molecules of contaminants, for example oil either from the hand or machine, are in the order of 100 Angstroms in length. Should these molecules be adsorbed in the leak, they would reduce the size of the hole and therefore reduce the leak rate to a point of apparent clogging. It should be noticed that according to the equation for molecular flow (Equation 10) the flow mode which should predominate in this range, the leakage rate is proportional to the cube of the leak diameter.

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*One centimeter is equal to 10^8 Angstrom units

3. Leak Detection and Measurement Techniques

a. Application of Instruments

In the next section some of the more common methods of leak detection are listed. It is extremely difficult to make general rules as to the situations in which the above leak detection methods are to be applied. Part of the art of leak detection consists of a person's ability to select the best leak detection method for a certain application.

Occasionally, equipment already installed on the apparatus may be profitably used for leak detection. For example, a space simulator requires leak detection, and part of the simulator's instrumentation is a partial pressure analyzer, i.e., a small mass spectrometer which measures the residual pressure of gases remaining in the system, this analyzer could be used as a leak detector. The partial pressures of various residual gases in the system would show whether the leakage consists of air entering the system, of water from one of the plumbing lines, one of various cryogenic fluids from the cooling baffles, or oil from the pumps. If air leakage is the case, the partial pressure analyzer could be used as a standard helium leak detector.

A short summary follows of various leak detection situations illustrating the most applicable methods to be used in certain cases. Leak detection instruments, like most instruments, should only be used within their design range. Instruments used to detect leakage rates smaller than they have been designed for, will cause leakages to be masked by the noise of the instrument,making the job very tedious. In addition, some instrument manufacturers are optimistic about the sensitivity of their instruments. Conversely, the use of an instrument on leaks larger than its designed range will cause the purchase of an instrument much more expensive than necessary. In this case, helium and halogen leak detectors will be slow in their leak detection procedure due to accidental poisoning or overflooding with excessive tracer gas.

i. Vacuum systems with leakages as small as 10^{-4} atm cc/sec.

1. Pressure rise in the system with isolation of various areas.
2. Tracer gas using thermocouple, Pirani, or ionization gauge.

ii. Vacuum system with leakage as small as 10^{-6} atm cc/sec.

1. Halogen leak detector with vacuum attachment.
2. Hydrogen leak detector.
3. Oxygen leak detector.
4. Argon leak detector.
5. Helium leak detector.

iii. Vacuum system with leakages as small as 10^{-10} atm cc/sec.

1. Helium leak detector.
2. Argon leak detector (only if volume of vacuum system is small).

iv. Systems which cannot be evacuated

1. Bubble testing - Small system: immersion
   - Large system: soap solution
2. Halogen leak detector.
3. Helium leak detector with probe.
4. Observation of pressure drop in system.
5. Small system - pressurize and observe weight change.

6. Small system - pressurize and place in vacuum system.

   a) Test by pump-down time

   b) Halogen leak detector

   c) Helium leak detector

   d) Argon leak detector

v. Many small sealed components

   1. Radioactive tracer leak test.

   2. Pressurize with helium or Freon* and place in vacuum system with helium or halogen leak detector. Sensitivity of this method is 10^{-6} times less than the radioactive gas method.

   3. Fluorescent dye. The sensitivity of this method is 10^{-6} times less than a halogen or helium leak detector.

b. Instrumentation for Leak Detection and Measurement

Leak detection and measurement instrumentation are quite varied. Some of their methods will be described in this section. Additional information on leak testing may be found in Chapter 5, Ref. 4 and Ref. 15. Four different methods of leak detection are categorized and explained:

   i. Physical observation of leakage.

   ii. Difference in pressure due to leakage.

   iii. Change in gauge readings due to the effect of tracer gas.

   iv. Detection of the tracer gas.

   i. Physical Observation of Leakage

      1. Sonic Detectors - Leak detectors are available to physically detect the sound made by the outflow of a gas, presumably

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*Trademark of DuPont

sensitivity of their instruments. Conversely, the use of an instrument on leaks larger than its designed range will cause the purchase of an instrument much more expensive than necessary. In this case, helium and halogen leak detectors will be slow in their leak detection procedure due to accidental poisoning or overflooding with excessive tracer gas.

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   1. Halogen leak detector with vacuum attachment.
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   3. Oxygen leak detector.
   4. Argon leak detector.
   5. Helium leak detector.

iii. Vacuum system with leakages as small as 10^{-10} atm cc/sec.

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   - a) Test by pump-down time
   - b) Halogen leak detector
   - c) Helium leak detector
   - d) Argon leak detector

v. Many small sealed components

1. Radioactive tracer leak test.
2. Pressurize with helium or Freon* and place in vacuum system with helium or halogen leak detector. Sensitivity of this method is 10^{-6} times less than the radioactive gas method.
3. Fluorescent dye. The sensitivity of this method is 10^{-6} times less than a halogen or helium leak detector.

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1. Sonic Detectors - Leak detectors are available to physically detect the sound made by the outflow of a gas, presumably

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*Trademark of DuPont

choked flow. Manufacturers stated sensitivity of these instruments is approximately 10^{-1} atm. cc/sec.

2. Fluorescent dyes.- A penetrating fluorescent dye solution is made which may be painted onto a weld and then wiped away. This dye will penetrate into any cracks and fisures. The material that is not wiped away is observed due to fluorescence, under ultraviolet light. This method of leak detection will display flaws in machining and joining. No quantitative estimates can be made as to the leak size which can be detected by this method.

3. Bubble Testing by Soap Solution - A container to be tested is pressurized and painted with a soap solution. Any leak can be seen by the growth of bubbles. The efficiency of this method depends upon: the observation abilities of the operator, the ability to completely wet the tested area, the surface tension of the soap solution, and the complexity of the part. It has been estimated that under proper conditions the sensitivity of this method is 10^{-4} atm cc/sec.

4. Bubble Testing by Immersion - A pressurized vessel may be immersed in a liquid; the bubbles rising to the surface will indicate a leak. This method is dependent on the pressure capability of the vessel, surface tension of the liquid and the size of the testing area. This method is obviously not suitable to large vessels. However, modifications can be made to cover one area by a liquid. This technique is simpler than soap solution testing because the observation abilities

of the operator are not as important. The sensitivity of this method is about 10^{-5} atm. cc/sec.

5. Halide Torch Leak Detector - The halide leak detector consists of a propane gas torch with a copper plate in the flame and a rubber tube supplying the flame with air. The system to be tested is pressurized with Freon gas and the end of the rubber tube which supplies air to the flame is passed over the suspected area. A leak is detected when the flame turns bright green, since a piece of copper in a flame containing halogen atoms gives off a characteristic green flame. This equipment is often used by household refrigerator repairmen because the refrigerant (Freon) acts as the tracer gas and the equipment is inexpensive. The sensitivity of this method is reported to be approximately 10^{-5} atm. cc/sec.

ii. Difference in pressure due to leakage

1. Pressure drop in the container - A container may be pressurized with a gauge attached to it which will show the pressure drop. This essentially is a method of measuring the leakage rate. The sensitivity of this method is defined by the equation:

$$Q = \frac{V \Delta P}{\theta} \qquad \text{Equation 38}$$

where Q = leakage rate sensitivity

V = container volume

ΔP = pressure differences, which may be measured

θ = time increment between readings

The ultimate sensitivity of this method is controlled not only by the length of the time increment and the sensitivity of the gauge, but also because temperature changes in the environment will produce independent pressure changes.

2. Pressure increase in vacuum system - A container can be placed in a vacuum system; the leakage rate can be determined by the pressure increase. Equation 38 may be used to calculate the sensitivity of this method providing the proper correction for outgassing and leakage within the vacuum system is made.

3. Ultimate pressure obtained in the vacuum system - If the container or leak is placed in the vacuum system and pumped through an orifice of known dimensions, the ultimate pressure obtained in such a system is:

$$Q = P_u S \qquad \text{Equation 39}$$

where Q = measured leakage

S = pumping speed of the system

P_u = ultimate pressure obtained.

The sensitivity of this method of leak detection is dependent on the magnitude of outgassing and the pumping speed of the vacuum system as compared with the leakage rate.

4. Argon leak detector - One commercially sold detector uses the pressure rise in a vacuum system to detect leaks. The leak detector consists of a vacuum system which uses a getter pump. This type of pumping is efficient for all but the inert gases. Argon or helium is therefore used as a tracer gas. When argon enters the vacuum system through the leak, the pump is not capable of gettering it efficiently and the pressure in the

system rises. The sensitivity of this type of pressure rise method is reported to be extremely high, 10^{-9} atm. cc/sec. The major disadvantage of this method of leak testing is that it is not readily applicable to large volume systems, because of the large amount of argon needed to be pumped from the air in the system.

3. Change in pressure gauge readings due to the effect of tracer gas

Because a large number of leak detection methods, involve the use of three types of vacuum gauges, it is convenient at this time to describe the three types of gauges involved.

Pirani Gauge - the heat conductivity of a gas is proportional to the pressure over a large range. The Pirani gauge consists of wire with electrical currents flowing through it. The resistance of this wire is dependent on its temperature. By the use of a Wheatstone bridge arrangement, using a sealed wire as a reference, the pressure of the system may be measured.

Thermocouple Gauge - This gauge uses the same principle for its measurement as the Pirani gage; i.e., the heat conductivity of a gas. In the thermocouple gauge the current passing through the wire remains constant and the temperature of the wire is measured by the thermocouple welded to it.

Ionization Gauge - An ionization gauge is a triode where an electrical current is passed between a cathode and the plate. The electrons passing from the cathode to the plate encounter residual gas molecules in their path.

The electrons striking these molecules ionize them and the current produced by these ions is measured as grid current. This current is dependent on the number of atoms encountered in the electron stream, and therefore is proportional to the pressure in the system.

1. Leak Testing with Pressure Gauges - If the system containing one of the pressure gauges described above is evacuated, leaks may be detected by using a tracer gas and observing the pressure. When the tracer gas enters the vacuum system, the composition of the gas within the system will change. Thus, the thermal conductance measured by the gauge will change. This pressure change may be interpreted as a tracer gas entering the leak and its location. There are many tracer gases which can be used in this technique. If a thermocouple or a Pirani gauge is used for pressure measurement, hydrogen or helium with their high heat conductivity would indicate a large rise in pressure when these gases enter the system. This indicated increase in pressure would be due to a two-fold effect; the actual rise in pressure because of increase in leakage rate with the tracer gas and the indicated increase due to their higher heat conductivity. Alternatively, acetone or alcohol could be used as the tracer fluid, in this case being painted on the suspected area, with a brush. A decrease in pressure would be observed, due to possible clogging of the leak with the liquid. This would produce a pressure drop and an indicated decrease due to the lower heat conductivity of the tracer which enters.

With the use of an ionization gauge, the ionization efficiency in the tracer gas should be different from that of the air.

Further discussions of these methods are cited in the references in the section b.

2. Hydrogen Sensitive Leak Detector - A hydrogen sensitive leak detector consists of an ionization gauge connected to the vacuum system by a heated paladium diaphragm. Hydrogen, which is used as the tracer gas, permeates through the hot paladium to the ion gage. The advantage of this system is that it is relatively insensitive to pressure changes. This detector has a reported sensitivity of about 10^{-8} atm. cc/sec.

3. Electron Emission Leak Detector - The electron emission from a tungsten or oxide coated filament decreases greatly upon contact with oxygen. This phenomenon, (Ref. 17), has been applied to leak detection. The sensitivity of this method, using oxygen as a tracer gas, is reported to be approximately 10^{-8} atm cc/sec.

4. The Halogen Leak Detector - Early investigations of thermionic emission showed that platinum, even in air, at red heat emits positive ions. This emission at any given anode temperature of positive ions in air is increased very markedly when vapors of compounds containing a halogen strike the electrode surface. This observation forms the basis of the halogen leak detector. Leak detectors using this principle are marketed by several companies. Two types of models exist. One type consists of a detector head mounted in the vacuum system and the halogen gas,

usually Freon, used as a tracer outside the vacuum system. A second type consists of a small gas pump probe; the system to be leak tested is pressurized with halogen-containing gas. The gas pump probe contains the detection apparatus. The sensitivity of this method of leak detection is approximately 10^{-6} atm. cc/sec. Special units are claimed to be as sensitive as 10^{-9} atm. cc/sec.

iii. Detection of the Tracer Gas

1. Helium Leak Detector - A very sensitive method for detection of leaks is the use of a mass spectrometer and helium as the tracer gas. The mass spectrometer is attached to the vacuum system and a probe of helium gas is passed around the suspected leak area. The mass spectrometer is set directly on the helium mass peak. Detection and measurement consists of observation of the intensity of the ion current. Helium is chosen as the tracer gas for the following reasons:
    1. Low value of M - the rate of effusion through the leak is greater than for any other gas except hydrogen.
    2. Helium occurs in the atmosphere only to the extent of one part per 200,000 parts of air.
    3. There is no possibility that an ion, due to any other gas will give an indication that can be mistaken for helium.

Several companies manufacture commercial leak detection equipment using this principle. The sensitivity of most of these units is 10^{-10} atm. cc/sec. One company manufactures a helium leak detector which operates on a pressure build-up by getter-ion pumping prior to detection of the peak. The sensitivity of this instrument is claimed to be 10^{-14} atm. cc/sec. Because the vacuum equipment in this apparatus is similar to the equipment in the argon leak detector previously described, (subsection b-4), this instrument could be used as a binary leak detector. For gross leaks the pressure build-up using an argon probe would be used. After all the large leaks were detected, helium gas could be used to hunt for the small leaks.

2. Helium Probe Method

Another method of using the helium leak detector is pressurizing the suspected area with helium and using a vacuum probe to collect air from outside the suspected leak area and pass it into the vacuum system containing the mass spectrometer. This method has a sensitivity of about 10^{-6} atm. cc/sec.

3. Leak Detection by Radioactivity - One nondestructive method of leak testing hermetically sealed components is by using a radioactive gas. This type of leak detecting equipment is commercially available. The basic principle involves the detection of radioactive Krypton 85, which has been allowed to diffuse into the leaking components. The components to be tested are placed in an activating tank and sealed. Air in the tank is evacuated and diluted. Krypton 85 is pumped into the tank to a pressure up to 7 atmospheres. The radioactive gas diffuses into the existing leaks in the component. After a prescribed soaking period, the Krypton is pumped out and returned to storage for reuse. Air is circulated over the components to remove any residual Krypton 85 from the external surface. - The components are then removed

from the activating tank and tested with a scintillation counter. Under favorable conditions, leakage rates in the order of 10^{-12} atm. cc/sec can be measured.

LIST OF SYMBOLS

A = Area of passage normal to flow.

A^o = Avogadro's number, number of molecules per mole.

$a = \frac{\pi}{8\eta}\left(\frac{d}{2}\right)^4$

$b = \frac{1}{6}\sqrt{\frac{2\pi RT}{M}}\, d^3$

C = Conductance of a passage.

C_1 = Conductance of a portion of a passage.

C_2 = Conductance of a portion of a passage.

C_3 = Conductance of a portion of a passage.

C_n = Conductance of a portion of a passage.

C_p = Heat capacity at constant pressure.

C_r = Heat capacity at constant volume.

d = Diameter of flow path

F = Velocity of fluid.

F_c = Speed of sound.

$\overline{F}$ = Average speed of individual molecules.

f = Friction factor.

g = Mass

$h = 1.24\sqrt{\frac{M}{RT}}\ \frac{d}{\eta}$

$j = \sqrt{\frac{M}{RT}}\ \frac{d}{\eta}$

K_p = Permeation rate constant.

ℓ = Length of passage.

$\Delta\ell$ = Increment of length of passage.

M = Molecular weight.

m = Mass of individual molecules.

N_k = Knudsen's number.

N_{Re} = Reynolds' number.

n = Number of molecules in a unit volume.

P = Pressure.

ΔP = Pressure drop.

P_a = Average pressure.

P_u = Ultimate pressure obtained in system.

P_1 = Pressure at point upstream in system.

P_2 = Pressure at point downstream in system.

Q = Mass flow.

R = Gas constant.

r = P_2/P_1

r_c = Critical pressure ratio. Ratio below which choked flow takes place.

S = Pumping speed.

T = Absolute temperature.

T_1 = Absolute temperature upstream of the orifice.

V = Volume

$\propto$ = Proportional to ....

γ = C_p/C_v

η = Absolute viscosity.

θ = Time increment.

λ = Mean free path.

ρ = Density.

σ = Molecular diameter.

ϕ = Surface tension.

Table I LEAKAGE CONVERSION FACTORS

micron x cc	1	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$	16	$1.6x10^{4}$	$8.5x10^{5}$	$1.2x10^{7}$	29	$2.9x10^{4}$	$1.5x10^{6}$	$2.2x10^{7}$	$1.0x10^{3}$	$1.0x10^{6}$	$5.2x10^{7}$	$7.6x10^{8}$	$2.8x10^{4}$	$2.8x10^{7}$	$1.5x10^{9}$	$2.1x10^{10}$
torr x cc	$1.0x10^{-3}$	1	52	$7.6x10^{2}$	$1.6x10^{-2}$	16	$8.5x10^{2}$	$1.2x10^{4}$	$2.9x10^{-2}$	29	$1.5x10^{3}$	$2.2x10^{4}$	1.0	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$	28	$2.8x10^{4}$	$1.5x10^{6}$	$2.1x10^{7}$
psi x cc	$1.9x10^{-5}$	$1.9x10^{-2}$	1	15	$3.1x10^{-4}$	0.31	16	$2.4x10^{2}$	$5.6x10^{-4}$	0.56	29	$4.4x10^{2}$	$1.9x10^{-2}$	19	$1.0x10^{3}$	$1.5x10^{4}$	0.53	$5.3x10^{2}$	$2.8x10^{4}$	$4.1x10^{5}$
atm x cc	$1.3x10^{-6}$	$1.3x10^{-3}$	$6.8x10^{-2}$	1	$2.1x10^{-5}$	$2.1x10^{-2}$	0.11	16	$3.8x10^{-5}$	$3.8x10^{-2}$	0.20	29	$1.3x10^{-3}$	1.3	68	$1.0x10^{3}$	$3.6x10^{-2}$	36	$1.9x10^{3}$	$2.8x10^{4}$
micron x in^{3}	$6.1x10^{-2}$	61	$3.2x10^{3}$	$4.6x10^{4}$	1	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$	1.8	$1.0x10^{3}$	$9.4x10^{4}$	$1.4x10^{6}$	61	$6.1x10^{4}$	$3.2x10^{6}$	$4.6x10^{7}$	$1.7x10^{3}$	$1.7x10^{6}$	$8.8x10^{7}$	$1.3x10^{9}$
torr x in^{3}	$6.1x10^{-5}$	$6.1x10^{-2}$	3.2	46	$1.0x10^{-3}$	1	52	$7.6x10^{2}$	$1.8x10^{-3}$	1.8	96	$1.4x10^{3}$	$6.1x10^{-2}$	61	$3.2x10^{3}$	$4.6x10^{4}$	1.7	$1.7x10^{3}$	$8.8x10^{4}$	$1.3x10^{6}$
psi x in^{3}	$1.2x10^{-6}$	$1.2x10^{-3}$	$6.1x10^{-2}$	0.89	$1.9x10^{-5}$	$1.9x10^{-2}$	1	15	$3.4x10^{-5}$	$3.4x10^{-2}$	1.8	26	$1.2x10^{-3}$	1.2	61	$8.9x10^{2}$	$3.2x10^{-2}$	32	$1.7x10^{3}$	$2.5x10^{4}$
atm x in^{3}	$7.9x10^{-8}$	$7.9x10^{-5}$	$4.1x10^{-3}$	$6.1x10^{-2}$	$1.3x10^{-6}$	$1.3x10^{-3}$	$6.8x10^{-2}$	1	$2.3x10^{-6}$	$2.3x10^{-3}$	0.12	1.8	$7.9x10^{-5}$	$7.9x10^{-2}$	4.1	61	$2.2x10^{-3}$	2.2	$1.2x10^{2}$	$1.7x10^{3}$
micron x fl.oz.	$3.4x10^{-2}$	34	$1.7x10^{3}$	$2.6x10^{4}$	0.55	$5.5x10^{2}$	$2.9x10^{4}$	$4.2x10^{5}$	1	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$	34	$3.4x10^{4}$	$1.8x10^{5}$	$2.6x10^{7}$	$9.6x10^{2}$	$9.6x10^{5}$	$4.9x10^{7}$	$7.3x10^{8}$
torr x fl.oz.	$3.4x10^{-5}$	$3.4x10^{-2}$	1.7	26	$5.5x10^{-4}$	0.55	29	$4.2x10^{2}$	$1.0x10^{-3}$	1	52	$7.6x10^{2}$	$3.4x10^{-2}$	34	$1.8x10^{3}$	$2.6x10^{4}$	0.96	$9.6x10^{2}$	$4.9x10^{4}$	$7.3x10^{5}$
psi x fl.oz.	$6.4x10^{-7}$	$6.4x10^{-4}$	$3.4x10^{-2}$	0.49	$1.0x10^{-5}$	$1.0x10^{-2}$	0.55	8.1	$1.9x10^{-5}$	$1.9x10^{-2}$	1	14.7	$6.4x10^{-4}$	0.64	34	$4.9x10^{2}$	$1.8x10^{-2}$	18	$9.6x10^{2}$	$1.4x10^{4}$
atm x fl.oz.	$4.4x10^{-8}$	$4.4x10^{-5}$	$2.3x10^{-3}$	$3.4x10^{-2}$	$7.2x10^{-7}$	$7.2x10^{-4}$	$3.7x10^{-2}$	0.55	$1.3x10^{-6}$	$1.3x10^{-3}$	$6.8x10^{-2}$	1	$4.4x10^{-5}$	$4.4x10^{-2}$	0.23	34	$1.2x10^{-3}$	1.2	65	$9.6x10^{2}$
micron x liters	$1.0x10^{-3}$	1.0	52	$7.6x10^{2}$	$1.6x10^{-2}$	16	$8.3x10^{2}$	$1.2x10^{4}$	$2.9x10^{-2}$	29	$1.5x10^{3}$	$2.2x10^{4}$	1	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$	28	$2.8x10^{4}$	$1.5x10^{6}$	$2.2x10^{7}$
torr x liters	$1.0x10^{-6}$	$1.0x10^{-3}$	$5.2x10^{-2}$	0.76	$1.6x10^{-5}$	$1.6x10^{-2}$	0.83	12	$2.9x10^{-5}$	$2.9x10^{-2}$	1.5	22	$1.0x10^{-3}$	1	52	$7.6x10^{2}$	$2.8x10^{-2}$	28	$1.5x10^{3}$	$2.2x10^{4}$
psi x liters	$1.9x10^{-8}$	$1.9x10^{-5}$	$1.0x10^{-3}$	0.15	$3.0x10^{-7}$	$3.0x10^{-4}$	$1.6x10^{-2}$	0.24	$5.5x10^{-7}$	$5.5x10^{-4}$	$2.9x10^{-}$[illegible]	0.43	$1.9x10^{-5}$	$1.9x10^{-2}$	1	14.7	$5.5x10^{-4}$	0.55	28	$4.3x10^{2}$
atm x liters	$1.3x10^{-9}$	$1.3x10^{-6}$	$6.8x10^{-5}$	$1.0x10^{-3}$	$2.1x10^{-8}$	$2.1x10^{-5}$	$1.1x10^{-3}$	$1.6x10^{-2}$	$3.8x10^{-8}$	$3.8x10^{-5}$	$1.9x10^{-3}$	$2.9x10^{-2}$	$1.3x10^{-6}$	$1.3x10^{-3}$	$6.8x10^{-2}$	1	$3.8x10^{-5}$	$3.8x10^{-2}$	1.9	28
micron x ft^{3}	$3.5x10^{-5}$	$3.5x10^{-2}$	1.8	27	$5.8x10^{-4}$	0.58	30	$4.4x10^{2}$	$1.0x10^{-3}$	1.04	54	$7.9x10^{2}$	$3.5x10^{-2}$	35	$1.8x10^{3}$	$2.7x10^{4}$	1	$1.0x10^{3}$	$5.2x10^{4}$	$7.6x10^{5}$
torr x ft^{3}	$3.5x10^{-8}$	$3.5x10^{-5}$	$1.8x10^{-3}$	$2.7x10^{-2}$	$5.8x10^{-7}$	$5.8x10^{-4}$	$3.0x10^{-3}$	0.44	$1.0x10^{-6}$	$1.0x10^{-3}$	$5.4x10^{-2}$	0.79	$3.5x10^{-5}$	$3.5x10^{-2}$	1.8	27	$1.0x10^{-3}$	1	52	$7.6x10^{2}$
psi x ft^{3}	$6.7x10^{-10}$	$6.7x10^{-7}$	$3.5x10^{-5}$	$5.1x10^{-4}$	$1.1x10^{-8}$	$1.1x10^{-5}$	$5.8x10^{-4}$	$9.9x10^{-3}$	$1.9x10^{-8}$	$1.9x10^{-5}$	$1.0x10^{-3}$	$1.5x10^{-2}$	$6.7x10^{-7}$	$6.7x10^{-4}$	$3.5x10^{-2}$	0.51	$1.9x10^{-5}$	$1.9x10^{-2}$	1	15
atm x ft^{3}	$4.6x10^{-11}$	$4.6x10^{-8}$	$2.4x10^{-6}$	$3.5x10^{-5}$	$7.5x10^{-10}$	$7.5x10^{-7}$	$3.9x10^{-5}$	$5.8x10^{-4}$	$1.4x10^{-9}$	$1.4x10^{-6}$	$7.1x10^{-5}$	$1.0x10^{-3}$	$4.6x10^{-8}$	$4.6x10^{-5}$	$2.4x10^{-3}$	$3.5x10^{-2}$	$1.3x10^{-6}$	$1.3x10^{-3}$	$6.8x10^{-2}$	1

seconds	1	60	$3.6x10^{3}$	$8.6x10^{4}$	$6.1x10^{5}$	$2.6x10^{6}$	$3.1x10^{7}$
minutes	$1.7x10^{-2}$	1	60	$1.4x10^{3}$	$1.0x10^{4}$	$4.3x10^{4}$	$5.2x10^{5}$
hours	$2.8x10^{-4}$	$1.7x10^{-2}$	1	24	$1.7x10^{2}$	$7.2x10^{2}$	$8.8x10^{3}$
days	$1.2x10^{-5}$	$6.9x10^{-4}$	$4.2x10^{-2}$	1	7	30	$3.7x10^{2}$
weeks	$1.6x10^{-6}$	$9.8x10^{-5}$	$5.9x10^{-3}$	0.14	1	4.3	52
months	$3.8x10^{-7}$	$2.3x10^{-5}$	$1.4x10^{-3}$	$3.3x10^{-2}$	0.23	1	12
years	$3.2x10^{-8}$	$1.9x10^{-6}$	$1.1x10^{-4}$	$2.8x10^{-3}$	$1.9x10^{-2}$	0.83	1

To convert leakage rate units, find the starting pressure x volume units on the left hand side of the chart. Move horizontally on that line, to the column which is 1 for those units. Move vertically to the line which contains the desired new units. Multiply the old leakage rate by the new units to obtain a new pressure x volume.

To convert the time units, obtain the time conversion factors in the above described manner and divide the leak rate by the appropriate conversion factor.

Example: Convert 5 psi x ft^{3}/month to atm x cc/sec

5 psi x ft^{3}/month x $1.9x10^{3}$ atm x cc/psi x ft^{3} x $1/2.6x10^{6}$ sec/month = $3.7 \text{ x } 10^{-3}$ atm-cc/sec

TABLE 2

MEAN FREE PATHS AND MOLECULAR DIAMETERS FOR VARIOUS MOLECULES

Molecule	Mean Free Path cm x 10^{-3} at 1 Torr and 25°C	Molecular Diameter cm x 10^{-8}
H_2	9.31	2.75
He	14.72	2.18
Ne	10.45	2.60
A	5.31	3.67
O_2	5.40	3.64
CO_2	3.34	4.65
H_2O	3.37	4.68
benzene	1.34	7.65
methane	4.15	4.19
ethane	2.53	5.37
propane	1.82	6.32
n-butane	1.46	7.06
n-pentane	1.19	7.82
n-hexane	1.03	8.42

TABLE 3

MOLAR HEAT CAPACITY OF GASES
(in calories per mole at 25°C and 1 atm)

Gas	C_p	C_v	$C_p/C_v = \gamma$
A	4.97	2.98	1.67
He	4.97	2.98	1.67
H_2	6.90	4.91	1.41
O_2	7.05	5.05	1.40
N_2	6.94	4.95	1.40
CO_2	8.96	6.92	1.29
NH_3	8.63	6.57	1.31
ethane	12.71	10.65	1.19
propane	-	-	1.13

TABLE 4

FLOW CHARACTERISTICS OF CIRCULAR CAPILLARY LEAKS (REF. 15)

	Air		Other Gases, Q/Q_{air}					
d, cm	Q, Torr x liters/sec*	P_2, Torr	He	CO_2	H_2	CH_4	Ne	
lower limit			7.7	0.53	6.9	1.07	2.45	$= \left(\frac{\eta}{\eta_{air}}\right)\left(\frac{M_{air}}{M}\right)^{1/2}$
1×10^{-6}	9.9×10^{-14}	3.7×10^{-3}	7.3	0.55				
3×10^{-6}	1.0×10^{-12}	4.1×10^{-3}	6.8	0.59				
1×10^{-5}	1.7×10^{-11}	6.3×10^{-3}	5.3	0.68				
3×10^{-5}	3.2×10^{-10}	1.3×10^{-2}	3.8	0.78				
1×10^{-4}	1.4×10^{-8}	5.5×10^{-2}	2.3	0.94				
3×10^{-4}	6.4×10^{-7}	0.26	1.6	1.1				
1×10^{-3}	6.0×10^{-5}	2.2	1.2	1.20				
3×10^{-3}	4.5×10^{-3}	18	1.0	1.22				
1×10^{-2}	0.47	170	0.93	1.24				
upper limit			0.93	1.24	2.07	1.67	0.58	$\frac{\eta_{air}}{\eta}$

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* Q is for a leak of one centimeter length. For a leak of any other size, the length of the leak in centimeters is divided by Q.

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